(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
1 May 2003 (01.05.2003)

PCT

(10) International Publication Number
WO 03/036348 A1

(51) International Patent Classification[7]: G02B 6/26, 6/35

(21) International Application Number: PCT/US02/33514

(22) International Filing Date: 17 October 2002 (17.10.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/999,838 24 October 2001 (24.10.2001) US

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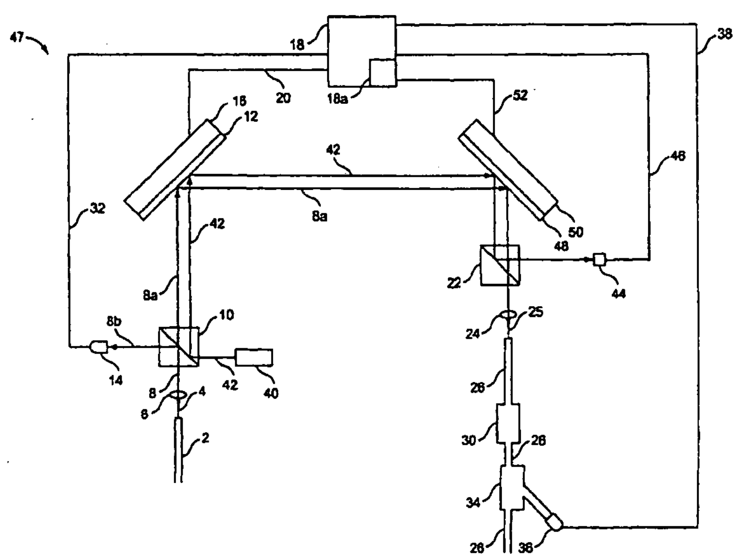
(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

[Continued on next page]

(54) Title: VARIABLE OPTICAL ATTENUATOR



(57) Abstract: A method of controllably attenuating a beam of light coupled into a port includes directing the beam of light against a mirror, and controlling an orientation of the mirror such that a predetermined fraction of the beam of light is coupled into the port. The predetermined fraction is less than a maximum fraction corresponding to optimal coupling of the beam of light into the port. The method may be implemented with a variable optical attenuator (47) including a first port (2), a second port (26), a mirror (12) located to direct light output by the first port (8a) to the second port, and a controller (18) coupled to the mirror to align it such that the predetermined fraction of light is coupled into the second port. The method may also be implemented with an optical switch.

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— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

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VARIABLE OPTICAL ATTENUATOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to optical fiber cross-connect switching. More particularly, it relates to load balancing in Dense Wavelength Division Multiplexing optical cross-connect systems.

2. Description of the Related Art

Associated with the information revolution is a need to increase by many orders of magnitude the rate of information transfer. This can be accomplished with optical fibers and the method of Dense Wavelength Division Multiplexing (DWDM), in which many wavelength channels, each including a different narrow band of wavelengths of light and each carrying different information, are multiplexed onto a single optical fiber using an optical multiplexer. Optical signals carried on the various wavelength channels may be separated at the output of the optical fiber with an optical demultiplexer.

Optical fiber cross-connect switches may be used to direct the optical signals on some or all of the wavelength channels on a particular optical fiber to other optical fibers. Such optical fiber cross-connect switches include those described in U.S. Patent Application Attorney Docket No. M-10967 US, U.S. Patent Application Attorney Docket No. M-11418 US, and U.S. Patent Application Attorney Docket No. M-11745 US, all of which are incorporated herein by reference in their entirety. Hence, optical signals on the various wavelength channels on an optical fiber may have originated at separate locations and traveled different distances in optical fiber. Since light is attenuated during transmission through optical fiber by an amount typically proportional to the distance traveled in optical fiber, the various wavelength channels on an optical fiber may carry different power levels.

Optical amplifiers such as Erbium Doped Fiber Amplifiers (EDFA) can amplify a wide wavelength band (spanning many wavelength channels), and thus compensate for transmission losses in optical fibers. If the power levels on the various wavelength channels carried by the optical fiber are not nearly equal at the input to the optical amplifier, however, the wavelength channel or channels of highest power may saturate the gain. Under such circumstances, the lower power wavelength channels might not be sufficiently amplified.

A variable optical attenuator is an optical device with which the amplitude or power level of an input optical signal may be attenuated by a variable amount to provide an output optical signal of a desired amplitude or power level. The power levels of the various wavelength channels on an optical fiber may be substantially equalized in a "load balancing" or "load equalization" process in which each wavelength channel is routed through a separate variable optical attenuator. Variable optical attenuators are described, for example, in U.S. Patents No. 5,864,643 and 6,130,984. These devices require the insertion of additional hardware into an optical network. The additional hardware may be expensive, requires additional physical space, and may introduce unwanted attenuation of the optical signals.

It would be desirable to incorporate the function of a variable optical attenuator into an optical network without the insertion of additional optical elements.

SUMMARY

A method of controllably attenuating a beam of light coupled into a port in accordance with an embodiment of the present invention includes directing the beam of light against a mirror, and controlling an orientation of the mirror such that a predetermined fraction of the beam of light is coupled into the port. The predetermined fraction is less than a maximum fraction corresponding to optimal coupling of the beam of light into the port. In one embodiment, this method is implemented with a variable optical attenuator including a first port, a second port, a mirror located to direct light output by the first port to the second port, and a

controller coupled to the mirror to align it such that the predetermined fraction of light is coupled into the second port. The ports may be or include optical fibers.

In one implementation, the variable optical attenuator includes a second mirror located to direct to the second port light output by the first port and reflected by the first mirror. The controller is also coupled to the second mirror to align it such that the predetermined fraction of light is coupled into the second port. Use of two controllable mirrors in the optical path of the light beam allows independent control of the position and angle of incidence of the light beam on the second port.

Control of the mirror or mirrors in the variable optical attenuator may be accomplished by numerous methods. In one implementation, the power of light coupled into the second port is measured, and an orientation of a mirror is controlled to maintain the power at a predetermined level. In another implementation, an orientation of a mirror corresponding to the predetermined fraction described above is selected from a look-up table. In another implementation, an alignment beam of light is directed against a mirror, and the orientation of the mirror is controlled to direct the alignment beam to a predetermined position on a position sensing detector. The predetermined position corresponds to the predetermined fraction described above.

In another embodiment, a variable optical attenuator includes a first plurality of ports, a second plurality of ports, a first plurality of mirrors disposed on a first surface, a second plurality of mirrors disposed on a second surface, and a controller coupled to align each of the first plurality of mirrors and each of the second plurality of mirrors such that predetermined fractions of light output by the first plurality of ports are coupled into separate ones of the second plurality of ports. The predetermined fractions are less than maximum fractions corresponding to optimal coupling of light output by the first plurality of ports into the second plurality of ports. This embodiment may be employed, for example, to load balance DWDM wavelength channels.

A method of equalizing the power levels of (load balancing) a plurality of channels multiplexed on an optical fiber in accordance with an embodiment of the present invention includes demultiplexing the channels from the optical fiber to

form a plurality of beams of light, with each beam of light formed from a separate channel, measuring the power level of each channel, directing each of the beams of light against a separate one of a plurality of mirrors, and controlling an orientation of one of the mirrors such that a predetermined fraction of the beam of light directed against that mirror is coupled into a port. The predetermined fraction is less than a maximum fraction corresponding to optimal coupling of the beam of light into the port.

Variable optical attenuators in accordance with embodiments of the present invention may be implemented in optical cross-connect switches. In such embodiments, the ports and mirrors of the variable optical attenuator may also support switching functions in the optical cross-connect switch. Optical cross-connect switches are typically designed and operated to achieve minimum insertion loss for all optical signals coupled into the switch. The inventors have recognized, however, that variable attenuation can be accomplished by separately controlling the insertion loss for the various optical signals by controllably misaligning mirrors used to switch the optical signals. Hence, the function of one or more variable optical attenuators may be advantageously integrated into an optical network without the insertion of additional optical elements.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates schematically a variable optical attenuator in accordance with an embodiment of the present invention.

Figure 2 illustrates schematically a portion of a variable optical attenuator in accordance with the embodiment of Figure 1.

Figure 3 illustrates schematically a variable optical attenuator in accordance with another embodiment of the present invention.

Figure 4 illustrates schematically an optical fiber cross-connect switch in which is implemented a variable optical attenuator in accordance with an embodiment of the present invention.

Figure 5 is a plot showing attenuation of the optical power coupled into an optical fiber versus misalignment of a light beam with respect to the optical fiber in accordance with an embodiment of the present invention.

Like reference numbers in the various figures denote same parts in the various embodiments. Dimensions in the figures are not necessarily to scale.

DETAILED DESCRIPTION

A variable optical attenuator in accordance with embodiments of the present invention variably attenuates light coupled into an optical fiber by controlled misalignment of one or more mirrors directing the light to the fiber. A number of embodiments will be described in which one or more optical signals are variably attenuated, and in which controlled misalignment of one or more mirrors is accomplished using, for example, measurements of the power of the attenuated optical signals or measurements of the position of control light beams separate from the optical signals to be attenuated.

Referring to Figure 1, optical fiber 2 carries light to be attenuated by a controlled amount in a variable optical attenuator 1 in accordance with an embodiment of the present invention. As is conventional in DWDM, optical fiber 2 may carry light having a plurality of wavelengths. In one implementation, the light carried by optical fiber 2 has wavelengths near about 1310 nanometers (nm) or about 1550 nm. Optical fiber 2 is, for example, a conventional Corning, Incorporated SMF-28 single mode optical fiber having a core diameter of about 8 microns (μm) and a cladding diameter of about 125 μm. Other optical fibers suitable for optical communications applications may also be used.

Optical fiber 2 outputs a diverging cone of light which is, for example, collimated or weakly focused by lens 6 to form light beam 8. Lens 6 is, for example, a conventional plano-convex lens formed from BK 7 optical glass and having a focal length of about 4 millimeters (mm). Light beam 8 is incident on beam splitter 10, which divides light beam 8 into light beam 8a incident on mirror 12 and light beam 8b incident on photodetector 14. Photodetector 14 is, for example, a conventional InGaAs photodiode. Suitable InGaAs photodiodes are

available from, for example, Hamamatsu Corporation of Bridgewater, New Jersey and Telcom Devices Corporation of Camarillo, California.

In one implementation, beam splitter 10 is a cube beam splitter formed from BK 7 optical glass and having a dielectric coating with a reflectivity of about 2% at infrared wavelengths of about 1200 nm to about 1700 nm. In another implementation, beam splitter 10 is a dichroic cube beam splitter formed from BK 7 optical glass and having a dielectric coating with a reflectivity of about 2% at infrared wavelengths of about 1200 nm to about 1700 nm and a reflectivity of about 40% to about 60%, preferably about 50%, at wavelengths of about 600 nm to about 850 nm. Such beam splitters are available, for example, from Harold Johnson Optical Laboratories, Inc. of Gardena, California. Suitable coatings for the beam splitter may be obtained, for example, from ZC&R Coatings For Optics, Inc. of Torrance, CA.

The reflectivity of such a dichroic beam splitter may be selected, for example, to allow at least partial separation of wavelengths of light used in telecommunications (e.g., 1200 nm - 1700 nm) from another range (e.g., 600 nm - 850 nm) of non-telecommunication wavelengths used for control light beams used in some embodiments as described below.

Referring again to Figure 1, mirror 12 directs light beam 8a, incident from beam splitter 10, through (optional) beam splitter 22, if it is present, to lens 24. In some implementations, lens 6 focuses light beam 8a to a waist at a location along light beam 8a between lens 6 and lens 24. Such focusing can maintain a relatively small diameter of light beam 8a throughout variable optical attenuator 1 and thus reduce uncontrolled optical loss from, e.g., diffraction.

Mirror 12 is coupled to actuator 16, which is controlled by control system 18 with electrical signals provided via electrical line 20 to orient mirror 12 in a range of arbitrary directions ($d\theta,d\varphi$). This range of orientations allows mirror 12 to direct light beam 8a onto lens 24 at a range of controlled angles with respect to optical axis 28 (Figures 2A-2C) of lens 24 and to a range of controlled positions on surface 25 of lens 24.

In one implementation, mirror 12 and actuator 16 are, respectively, a micro-electro-mechanical systems (MEMS) micro mirror and a MEMS actuator as described, for example, in U.S. Patent Application Serial Number 09/779,189 incorporated herein by reference in its entirety. Other micro mirrors may also be used. In such an implementation, mirror 12 may be a freely rotatable MEMS micro mirror actuated by, for example, electrostatic, electromagnetic, piezoelectric, or thermal actuation means. Mirror 12 may be, for example, approximately elliptical with major and minor diameters of about 1.0 mm and about 0.9 mm, respectively. Control system 18 may be, for example, a control system for a MEMS based optical switch such as, for example, control systems disclosed in U.S. Patent Application Attorney Docket No. M-11419 US and U.S. Patent Application Attorney Docket No. M-11502 US, both of which are incorporated herein by reference in their entirety.

In other implementations, mirror 12 may be a conventional mirror having a metal or dielectric coating highly reflective at wavelengths of about 1200 nm to about 1700 nm. Actuator 16 may be a conventional mirror mount actuated by, for example, conventional stepper motors or conventional piezoelectric actuators. Control system 18 may include, for example, a microprocessor and a conventional stepper motor driver or a conventional piezoelectric driver.

Lens 24 focuses light beam 8a, incident from mirror 12, onto optical fiber 26. In one implementation, for example, surface 25 of optical fiber 26 is approximately at the focal plane of lens 24. Referring to Figures 2A-2C, lens 24 is positioned with its optical axis 28 approximately centered on the core 26a of optical fiber 26. Lens 24 may be, for example, a conventional plano-convex lens formed from BK 7 optical glass and having a focal length of about 4 mm. Optical fiber 26 includes cladding 26b surrounding core 26a.

One of ordinary skill in the art will recognize that lens 24 may couple light beam 8a into a core (e.g., fundamental) optical mode of optical fiber 26 and/or into a cladding mode of optical fiber 26. The power distribution of light in a core mode of optical fiber 26 is concentrated in core 26a, although a portion of the power distribution of such a core mode propagates in cladding 26b. Light coupled into a

core mode can propagate long distances with little attenuation. In contrast, the power distribution of a cladding mode of optical fiber 26 is concentrated in cladding 26b.

Only that portion of light beam 8a incident on core 26a of optical fiber 26 at angles with respect to optical axis 28 less than the acceptance angle (determined by the refractive indices of core 26a and cladding 26b) of optical fiber 26 will be efficiently coupled into a core mode of optical fiber 26. Hence, the fraction of light beam 8a coupled into a core mode of optical fiber 26 depends on the location at which light beam 8a is incident on lens 24 and the angle that light beam 8a makes with respect to optical axis 28. In Figure 2A, for example, light beam 8a is incident on the approximate center of lens 24 approximately parallel to optical axis 28 and focused entirely onto core 26a within the acceptance angle θ_A indicated by dashed lines 27. Thus, light beam 8a is approximately aligned for maximum coupling into a core mode of optical fiber 26. The acceptance angle of optical fiber 26 in air may be, for example, about 7.5° (numerical aperture of about 0.13). One of ordinary skill in the art will recognize that the maximum optical power coupled into a core mode of optical fiber 26 is typically less than the total optical power of light beam 8a as a result of, for example, Fresnel reflection losses at surface 25.

In contrast, in Figure 2B, light beam 8a is incident on lens 24 at an angle θ with respect to optical axis 28 sufficiently large that light beam 8a misses core 26a and is focused entirely onto cladding 26b. Hence, little or none of light beam 8a is coupled into a core mode of optical fiber 26. Light coupled into a cladding mode of optical fiber 26 is subsequently removed, for example, by a conventional cladding mode stripper 30 (Figure 1). One of ordinary skill in the art will recognize that light coupled into cladding modes of an optical fiber is typically rapidly attenuated during transmission, particularly if the optical fiber is coiled or otherwise bent. Thus, in other implementations cladding mode stripper 30 is not used. Since light coupled into a cladding mode of optical fiber 26 is subsequently removed or otherwise attenuated, light described herein as being coupled into

optical fiber 26 refers to light coupled into a core mode of optical fiber 26 rather than into, for example, a cladding mode of optical fiber 26.

Figures 2A and 2B show alignments of light beam 8a resulting in, respectively, approximately minimum attenuation and approximately maximum attenuation of the light coupled into optical fiber 26. Control system 18 may control the orientation of mirror 12 to achieve alignments of light beam 8a intermediate between those of Figures 2A and 2B, and thus vary the attenuation of the light coupled into optical fiber 26 between the approximate minimum and approximate maximum levels of attenuation. In Figure 2C, for example, light beam 8a is incident on lens 24 at an angle θ with respect to optical axis 28 smaller than that of Figure 2B and focused to overlap both core 26a and cladding 26b of optical fiber 26. A fraction of light beam 8a focused onto surface 25 at angles less than the acceptance angle of optical fiber 26 will be coupled into a core mode of optical fiber 26. Another fraction of light beam 8a may be coupled into a cladding mode of optical fiber 26 and subsequently removed as described above.

Referring to Figure 5, curve 29 is a plot, for one implementation, of the attenuation of the optical power coupled into optical fiber 26 as a function of the offset of the center of light beam 8a at surface 25 from the center of core 26a of optical fiber 26. In this implementation, lens 24 has a focal length of about 4 mm, light beam 8a has a diameter of about 0.8 mm at lens 24, core 26a of optical fiber 26 has a diameter of about 8 μm, and surface 25 is approximately at the focal plane of lens 24. As curve 29 indicates, an offset of about 18 μm between the center of the focused beam and the center of optical fiber 26 in this implementation results in an attenuation of about 60 decibels (dB). This offset corresponds to a misalignment of light beam 8a with respect to optical axis 28 (Figures 2A-2C) of about 0.25°. Such a misalignment of light beam 8a can be achieved with a misalignment of mirror 12 of about 0.125°, since the angular displacement of light beam 8a is twice that of mirror 12.

In many optical communication applications the maximum optical attenuation required is about 30 dB. The slope of curve 29 at about 30 dB attenuation, represented by line 31, is about 1 dB of attenuation per 0.22 μm of

offset. This corresponds to about 3 dB per 0.01° misalignment of light beam 8a with respect to optical axis 28. Hence, control of the orientation of mirror 12 with a resolution of better than about 0.005° allows control of the attenuation of the power of light coupled into optical fiber 26 with a resolution better than about 3 dB. Such angular resolution may be achieved, for example, in optical fiber cross-connect switches described in U.S. Patent Application Attorney Docket No. M-10967 US, U.S. Patent Application Attorney Docket No. M-11418 US, and U.S. Patent Application Attorney Docket No. M-11745 US. Of course, the resolution with which the attenuation is controlled improves as the angular resolution with which the mirror is controlled is improved. Attenuation curves for other implementations are similar to curve 29.

Controlled misalignment of mirror 12 to attenuate light coupled into optical fiber 26 may be accomplished by numerous methods. Referring again to Figure 1, control system 18 receives electrical signals corresponding to the optical power in light beam 8b (and thus in light beam 8a) from photodetector 14 via electrical line 32. Control system 18 determines from these electrical signals the amount by which light beam 8a is to be attenuated. In one embodiment, (optional) conventional fiber coupler 34 directs a portion of the light coupled into optical fiber 26 to (optional) photodetector 36. Photodetector 36, which may be a conventional InGaAs photodiode, provides a signal corresponding to the optical power coupled into optical fiber 26 to control system 18 via electrical line 38. Control system 18 controls the orientation of mirror 12 such that the electrical signals provided by photodetector 36 indicate that the light coupled into optical fiber 26 is attenuated to the desired power level. Hence, in this embodiment control system 18, actuator 16, mirror 12, and photodetector 36 form a feedback loop by which attenuation of the light coupled into optical fiber 26 is controlled.

In another embodiment, a look-up table stored in a computer readable medium (memory 18a) in control system 18 relates the orientation of mirror 12 to the attenuation of the light coupled into optical fiber 26. In this embodiment, control system 18 determines from the electrical signals received from photodetector 14 the amount by which light beam 8a is to be attenuated, reads the

required orientation of mirror 12 from the look-up table (which contains information correlating the amount of attenuation to the mirror's orientation), and controls actuator 16 to orient mirror 12 accordingly. The look-up table may be generated by measuring, with photodetectors 14 and 36, for example, the attenuation of light coupled into optical fiber 26 for each of a series of different orientations of mirror 12.

In other embodiments, controlled misalignment of mirror 12 is accomplished using measurements of the position of one or more control light beams separate from the optical signals to be attenuated. In these embodiments, mirror 12 may be controlled, for example, using methods similar or identical to methods for controlling the orientations of mirrors in an optical fiber cross-connect switch disclosed in the following U.S. Patent Applications: Attorney Docket No. M-10967 US, Attorney Docket No. M-11418 US, Attorney Docket No. M-11419 US, Attorney Docket No. M-11502 US, and Attorney Docket No. M-11745 US.

In one implementation, for example, laser 40 (Figure 1) outputs control light beam 42 incident on dichroic beam splitter 10. In some implementations, the wavelength of control light beam 42 is a wavelength not typically used in telecommunications. In one implementation, for example, laser 40 is a conventional laser diode emitting light having a wavelength of about 660 nm. Dichroic beam splitter 10 reflects light beam 42 to mirror 12, which directs control light beam 42 to dichroic beam splitter 22. Dichroic beam splitter 22 reflects control light beam 42 to position sensing detector 44. Thus, the position at which control light beam 42 is incident on position sensing detector 44 is determined by the orientation of mirror 12. Dichroic beam splitter 22 is, for example, substantially identical to dichroic beam splitter 10. Suitable position sensing detectors are available, for example, from UDT Sensors, Inc. of Hawthorne, California and from Pacific Silicon Sensor, Inc. of Westlake Village, CA.

Position sensing detector 44 provides a signal indicating the position at which control light beam 42 is incident on it to control system 18 via electrical line 46. A look-up table stored in memory 18a in control system 18 relates the attenuation of the light coupled into optical fiber 26 to the position at which control

light beam 42 is incident on position sensing detector 44. In this implementation, control system 18 determines from the electrical signals received from photodetector 14 the amount by which light beam 8a is to be attenuated, determines from the look-up table the corresponding position on position sensing detector 44 to which control light beam 42 is to be directed, and controls the orientation of mirror 12 to direct control light beam 42 to that position. The look-up table used in this implementation may be generated by measuring the attenuation of light coupled into optical fiber 26 and the position at which control light beam 42 is incident on position sensing detector 44 for each of a series of orientations of mirror 12.

Variable optical attenuator 1 of Figure 1 includes only one mirror (mirror 12) having an orientation controlled by control system 18 in a range of directions ($d\theta$,$d\varphi$). The angle of incidence of light beam 8a on surface 25 and the location on surface 25 at which light beam 8a is incident (Figures 2A-2C) cannot be independently controlled with this single controlled mirror.

In other embodiments, light beam 8a is directed to optical fiber 26 by two or more mirrors having orientations controlled by controller 18. For example, variable optical attenuator 47 shown in Figure 3 includes, in addition to the elements shown in Figure 1, mirror 48 coupled to actuator 50. Actuator 50 is controlled by control system 18 with electrical signals provided via electrical line 52 to orient mirror 48 in a range of arbitrary directions ($d\theta$,$d\varphi$). Either or both of mirrors 12 and 48 can be controllably misaligned, by the methods described above, to variably attenuate light coupled into optical fiber 26. The use of two controllable mirrors in the optical path of light beam 8a allows independent control of the angle of incidence of light beam 8a on surface 25 and the location on surface 25 at which light beam 8a is incident. This may result in better control of light coupled into optical fiber 26. In some embodiments, lens 6 focuses light beam 8a to a waist at a location along light beam 8a between mirror 12 and mirror 48. Such focusing can maintain a relatively small diameter of light beam 8a throughout variable optical attenuator 47 and thus reduce uncontrolled optical loss.

Variable optical attenuators in accordance with embodiments of the present invention may be implemented within optical fiber cross-connect switches such as those described in U.S. Patent Application Attorney Docket No. M-10967 US, U.S. Patent Application Attorney Docket No. M-11418 US, and U.S. Patent Application Attorney Docket No. M-11745 US. In particular, mirrors 12 and 48 (Figure 3) may be mirrors in an optical fiber cross-connect switch oriented to couple light from an input port (optical fiber 2) to an output port (optical fiber 26). Although Figures 1 and 3 show only a single input optical fiber 2 and a single output optical fiber 26, an optical fiber cross-connect switch within which a variable optical attenuator is implemented in accordance with an embodiment of the present invention typically has a plurality of inputs and a plurality of outputs. In a typical optical path through such a switch, light entering the switch through an input port is incident on a corresponding first micro-mechanical mirror in a first two dimensional array of micro-mechanical mirrors. The first micro-mechanical mirror, which can be oriented in a range of arbitrary directions ($d\theta$,$d\varphi$), is tilted to direct the light to a second micro-mechanical mirror in a second two dimensional array of micro-mechanical mirrors. The second micro-mechanical mirror, which can also be oriented in a range of arbitrary directions ($d\theta$,$d\varphi$), is tilted to direct the light to a corresponding output port and hence out of the switch.

The light may be switched from the output port to which it is initially directed to another output port by reorienting the first micro-mechanical mirror to direct the light to another (i.e., a third) micro-mechanical mirror in the second array of micro-mirrors, and orienting the third micro-mechanical mirror to direct the light to its corresponding output port. The micro-mechanical mirrors may be optimally aligned to couple a maximum amount of light into an output port, or controllably misaligned to variably attenuate the light coupled into an output port. Advantageously, a variable optical attenuator function can be thereby added to an optical network without the insertion of additional optical elements, as power sensing functions such as those provided by beam splitter 10 and photodetector 14 (Figure 1) are typically present in such switches for control and monitoring

purposes. In this way, light entering the switch at any input port can be directed to any output port with the proper attenuation.

Referring to Figure 4, for example, optical fiber cross-connect switch 53 (substantially similar to those described in U.S. Patent Application Attorney Docket No. M-10967 US, U.S. Patent Application Attorney Docket No. M-11418 US, and U.S. Patent Application Attorney Docket No. M-11745 US) routes light carried by any one of N input optical fibers 54-1 - 54-N to any one of N output optical fibers 56-1 - 56-N and also performs variable optical attenuation functions in accordance with an embodiment of the present invention. In the implementation shown in Figure 4, the number of input optical fibers equals the number of output optical fibers. Other implementations include N input optical fibers and P output optical fibers, with either $N < P$ or $N > P$. Typically, both N and P are greater than about 1000. In one implementation, for example, N is about 1200 and $P = N$.

Optical fibers 54-1 - 54-N output diverging cones of light which are collimated or weakly focused by, respectively, lenses 60-1 - 60-N to form, respectively, light beams 62-1 - 62-N incident on beam splitter 10. Although for convenience of illustration optical fibers 54-1 - 54-N are shown in Figure 4 arranged in a single row, typically the ends of optical fibers 54-1 - 54-N are arranged in a two dimensional array. Lenses 60-1 - 60-N may be identical to lens 6 of Figure 1. Alternatively, lenses 60-1 - 60-N may be lenslets (small lenses) arranged in a two dimensional lenslet array sometimes called a microlens array.

Beam splitter 10 divides light beams 62-1 - 62-N into light beams 66-1 - 66-N and light beams 68-1 - 68-N. Light beams 66-1 - 66-N are incident on, respectively, lenses 70-1 - 70-N which focus them onto separate spots on input sensor 72. Input sensor 72 detects the intensity of each of light beams 66-1 - 66-N and provides corresponding electrical signals to control system 18 via bus 74. Input sensor 72 is, for example, a SU128-1.7RT infrared camera having a 128 x 128 pixel array available from Sensors Unlimited, Inc. of Princeton, New Jersey.

Light beams 68-1 - 68-N are incident on, respectively, micro mirrors 76-1 - 76-N of micro mirror array 76. Typically, micro mirrors 76-1 - 76-N are arranged in a two dimensional array corresponding to that of lenses 60-1 - 60-N and optical

fibers 54-1 - 54- N. In some implementations the pitch of micro mirrors 76-1 - 76-N in a direction along mirror array 76 parallel to the planes of incidence of light beams 68-1 -68-N (defined by light beams 68-1 - 68-N and axes normal to mirror array 76 at the points at which the light beams intersect mirror array 76) is elongated compared to the corresponding pitch of lenses 60-1 - 60-N such that light beams 68-1 - 68-N are incident approximately centered on micro mirrors 76-1 - 76-N. The orientations of micro mirrors 76-1 - 76-N are individually controllable over a range of arbitrary angles ($d\theta$,$d\varphi$) by control system 18 with electrical signals transmitted via bus 78. Micro mirror array 76 is, for example, a MEMS micro mirror array described in U.S. Patent Application Serial No. 09/779,189.

In the illustrated embodiment, micro mirrors 76-1 - 76-N reflect light beams 68-1 - 68-N, respectively, onto fold mirror 80. Fold mirror 80 reflects light beams 68-1 - 68-N onto micro mirror array 82. Micro mirror array 82 includes N micro mirrors 82-1 - 82-N. The orientations of micro mirrors 82-1 - 82-N are individually controllable over a range of arbitrary angles ($d\theta$,$d\varphi$) by control system 18 with electrical signals transmitted via bus 83. In one implementation, micro mirror arrays 76 and 82 are substantially identical.

In the illustrated embodiment each of micro mirrors 76-1 - 76-N is controllable to reflect a light beam incident on it from the corresponding one of optical fibers 54-1 - 54-N to any one of micro mirrors 82-1 - 82-N via fold mirror 80. Hence, control system 18 can control the orientations of micro mirrors 76-1 - 76-N to reflect, via fold mirror 80, any one of light beams 68-1 - 68-N onto the approximate center of any one of micro mirrors 82-1 - 82-N. For example, Figure 4 shows light beams 68-1, 68-2, and 68-N reflected to, respectively, micro mirrors 82-K, 82-J, and 82-I. Micro mirrors 82-I, 82-J, and 82-K, which need not be adjacent to one another, may be any of micro mirrors 82-1 - 82-N. In other embodiments micro mirrors 76-1 - 76-N are controllable to reflect light beams 68-1 - 68-N to any one of micro mirrors 82-1 - 82-N without the use of a fold mirror such as fold mirror 80. In some such embodiments, for example, micro mirrors 76-1 - 76-N may reflect light beams 68-1 - 68-N directly to any one of micro mirrors 82-1 - 82-N.

Control system 18 controls the orientations of micro mirrors 82-1 - 82-N to reflect the light beams incident on them from micro mirror array 76 to, respectively, lenses 84-1 - 84-N. Figure 4 shows micro mirrors 82-I, 82-J, and 82-K reflecting, respectively, light beams 68-N, 68-2, and 68-1 to, respectively, lenses 84-I, 84-J, and 84-K. It should be understood, however, that each particular one of micro mirrors 82-1 - 82-N is controlled to reflect whichever one of light beams 68-1 - 68-N is incident on it to the lens 84-1 - 84-N corresponding to that particular micro mirror. For example, micro mirror 82-1 is controlled to reflect whichever one of light beams 68-1 - 68-N is incident on it to lens 84-1.

Lenses 84-1 - 84-N focus light beams reflected by, respectively, micro mirrors 82-1 - 82-N onto, respectively, optical fibers 56-1 - 56-N. Lenses 84-1 - 84-N may be, for example, substantially identical to lenses 60-1 - 60-N.

Control system 18 determines from the electrical signals provided by input sensor 72 the amount by which light beams 60-1 - 60-N must be attenuated, and controls the orientation of micro mirrors 76-1 - 76-N and 82-1 - 82-N by, for example, the methods disclosed above (e.g., using control light beams and position sensing detectors) to variably attenuate and/or switch the light beams between output optical fibers 56-1 - 56-N.

In one embodiment, variable attenuation functions of optical cross-connect switch 53 are used to substantially equalize (load balance) the power levels of M Dense Wavelength Division Multiplexing wavelength channels on a single optical fiber, where $M \leq N$ (N the number of input ports). The wavelength channels are demultiplexed from the optical fiber with a conventional optical demultiplexer, and each coupled onto a separate one of M of the input optical fibers 54-1 - 54-N. Control system 18 determines the power levels of the M wavelength channels from the electrical signals it receives from input sensor 72, and controls mirror arrays 76 and 82 to route each of the M light beams corresponding to the various wavelength channels to a separate one of M of the output optical fibers 56-1 - 56-N. The lowest power wavelength channel is routed to its corresponding output optical fiber with, for example, approximately minimal attenuation. The power levels of the other wavelength channels are attenuated, for example, to approximately that of the

lowest power wavelength channel by controllably misaligning the micro mirrors of mirror arrays 76 and 82 as described above. A conventional optical multiplexer coupled to the M output optical fibers then multiplexes the wavelength channels onto a single optical fiber.

While the present invention is illustrated with particular embodiments, the invention is intended to include all variations and modifications falling within the scope of the appended claims.

CLAIMS

We claim:

1. A variable optical attenuator comprising:

a first port;

a second port;

a mirror located to direct light output by said first port to said second port; and

a controller coupled to said mirror to align said mirror such that a predetermined fraction of light output by said first port is coupled into said second port, wherein said predetermined fraction is less than a maximum fraction corresponding to optimal coupling of said light into said second port.

2. The variable optical attenuator of Claim 1, wherein said first port and said second port include optical fibers.

3. The variable optical attenuator of Claim 1, wherein said first port is one of a first plurality of ports and said second port is one of a second plurality of ports.

4. The variable optical attenuator of Claim 1, wherein said mirror is included in an optical cross-connect switch.

5. The variable optical attenuator of Claim 1, wherein said controller controls an orientation of said mirror with an angular resolution better than about 0.005°.

6. The variable optical attenuator of Claim 1, further comprising a splitter located to divide said light output by said first port into at least two portions, and a detector located to detect one of said portions.

7. The variable optical attenuator of Claim 1, further comprising a detector coupled to said second port to detect at least a portion of light coupled into said second port.

8. The variable optical attenuator of Claim 1, further comprising a light source and a position sensing detector, said mirror reflecting light output by said light source to said position sensing detector.

9. The variable optical attenuator of Claim 8, wherein said light source comprises a laser.

10. The variable optical attenuator of Claim 1, wherein said mirror is a first mirror, further comprising a second mirror located to direct to said second port light output by said first port and reflected by said first mirror.

11. The variable optical attenuator of Claim 10, wherein said controller is coupled to said second mirror to align said second mirror such that said predetermined fraction of light output by said first port is coupled into said second port.

12. A method of controllably attenuating a beam of light coupled into a port, the method comprising:

directing said beam of light against a mirror; and

controlling an orientation of said mirror such that a predetermined fraction of said beam of light is coupled into said port;

wherein said predetermined fraction is less than a maximum fraction corresponding to optimal coupling of said beam of light into said port.

13. The method of Claim 12, wherein said port includes an optical fiber.

14. The method of Claim 12, wherein said port is included in an optical cross-connect switch.

15. The method of Claim 12, wherein said mirror is included in an optical cross-connect switch.

16. The method of Claim 12, further comprising measuring a power of said beam of light, and determining from said power an amount by which to attenuate said beam of light.

17. The method of Claim 12, further comprising measuring a power of light coupled into said port, and controlling said mirror to maintain said power at a predetermined level.

18. The method of Claim 12, further comprising selecting from a look-up table an orientation of said mirror corresponding to said predetermined fraction.

19. The method of Claim 12, wherein said beam of light is a first beam of light, further comprising directing another beam of light against said mirror, and controlling said orientation of said mirror to reflect said other beam of light to a predetermined position on a position sensing detector, said predetermined position corresponding to said predetermined fraction of said first beam of light.

20. The method of Claim 19, further comprising selecting said predetermined position from a look-up table.

21. The method of Claim 12, wherein said mirror is a first mirror, further comprising reflecting said beam of light to a second mirror and controlling an orientation of said second mirror such that said predetermined fraction of said beam of light is coupled into said port.

22. A variable optical attenuator comprising:

a first plurality of ports;

a second plurality of ports;

a first plurality of mirrors disposed on a first surface;

a second plurality of mirrors disposed on a second surface; and

a controller coupled to align each of said first plurality of mirrors and each of said second plurality of mirrors such that predetermined fractions of light output by said first plurality of ports are coupled into separate ones of said second plurality of ports;

wherein at least a subset of said predetermined fractions are less than maximum fractions corresponding to optimal coupling of light output by said first plurality of ports into said second plurality of ports.

23. The optical switch of Claim 22, wherein said first plurality of ports and said second plurality of ports each includes greater than about 1000 ports.

24. The optical switch of Claim 22, wherein said first plurality of mirrors and said second plurality of mirrors each includes greater than about 1000 mirrors.

25. The optical switch of Claim 22, wherein said controller controls an orientation of each of said first plurality of mirrors and each of said second plurality of mirrors with an angular resolution better than about 0.005°.

26. A method of equalizing the power levels of a plurality of channels multiplexed on an optical fiber, the method comprising:

demultiplexing said channels from said optical fiber to form a plurality of beams of light, each beam of light formed from a separate channel;

measuring the power level of each channel;

directing each of said beams of light against a separate one of a plurality of mirrors; and

controlling an orientation of one of said mirrors such that a predetermined fraction of said beam of light directed against said one of said mirrors is coupled into a port, said predetermined fraction less than a maximum fraction corresponding to optimal coupling into said port.

27. The method of Claim 26, wherein each of said channels includes a separate range of wavelengths of light.

28. The method of Claim 26, further comprising determining which of said channels has the lowest power level on said optical fiber.

29. The method of Claim 28, wherein a beam of light formed from said lowest power level channel is coupled into another port with about minimum attenuation.

30. The method of Claim 28, wherein a power of said predetermined fraction of said beam of light about equals a power of light from said lowest power level channel coupled into another port.

31. The method of Claim 26, further comprising multiplexing said channels onto another optical fiber.

32. The method of Claim 26, wherein said plurality of mirrors is a first plurality of mirrors, further comprising controlling an orientation of each of said first plurality of mirrors to direct each of said beams of light against a separate one of a second plurality of mirrors.

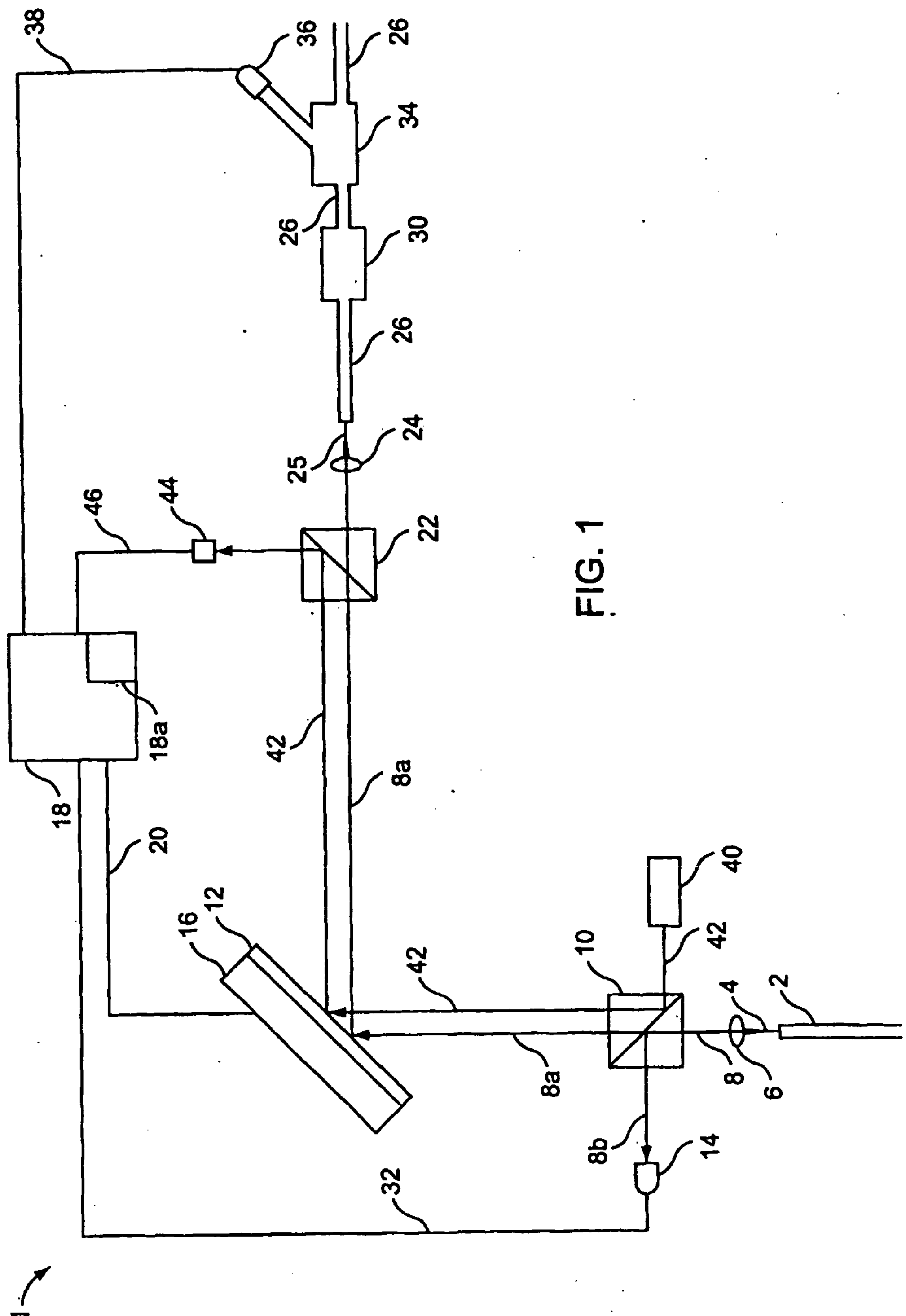
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FIG. 1

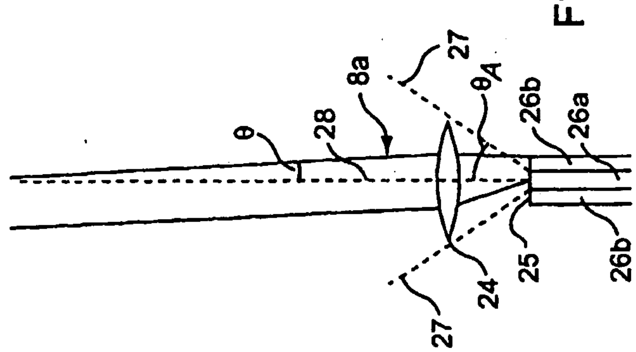

FIG. 2C

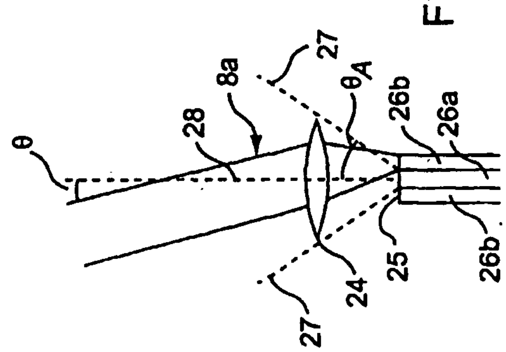

FIG. 2B

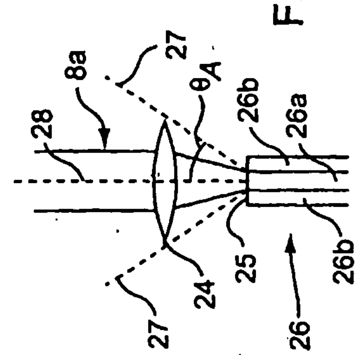

FIG. 2A

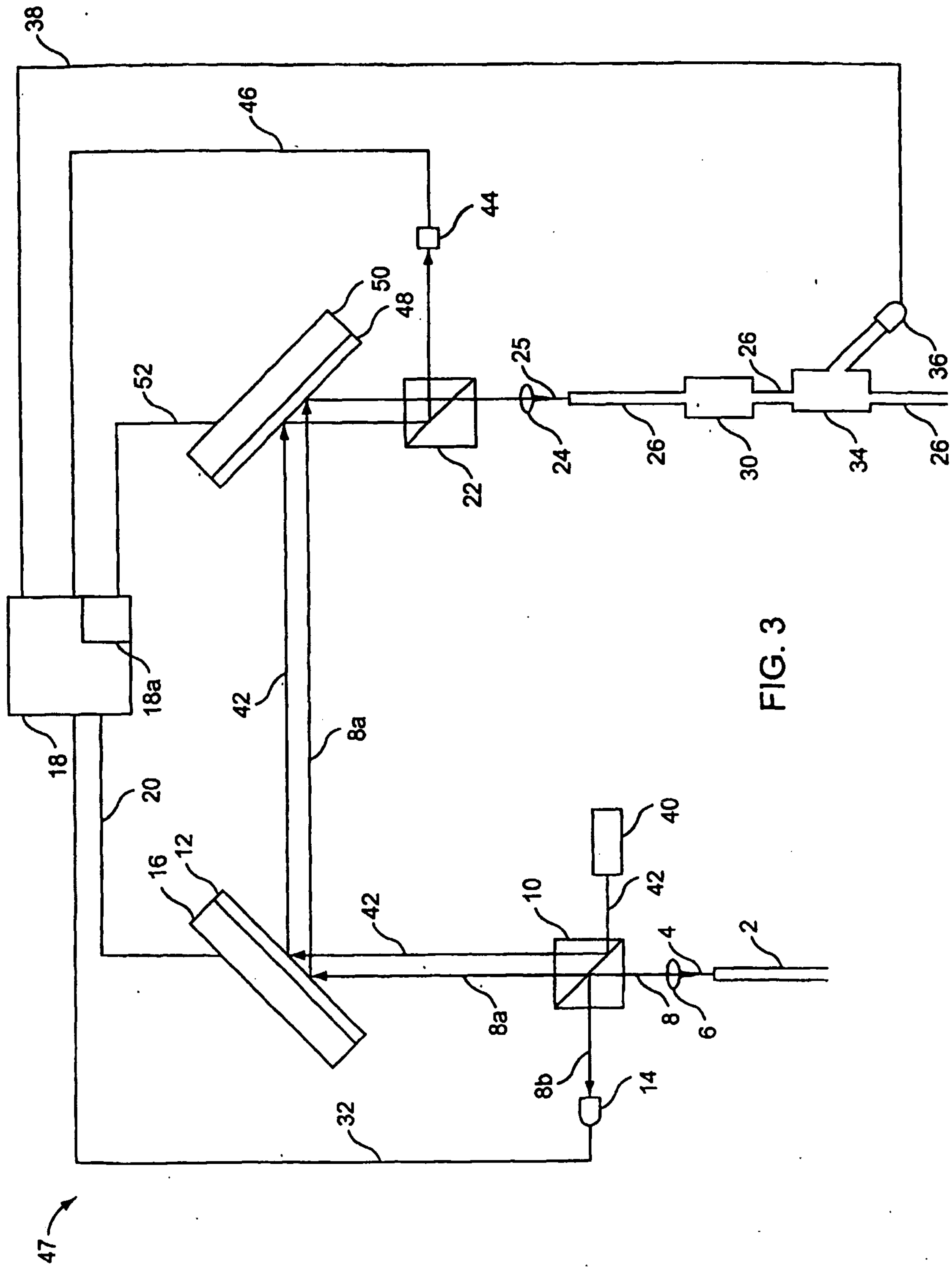
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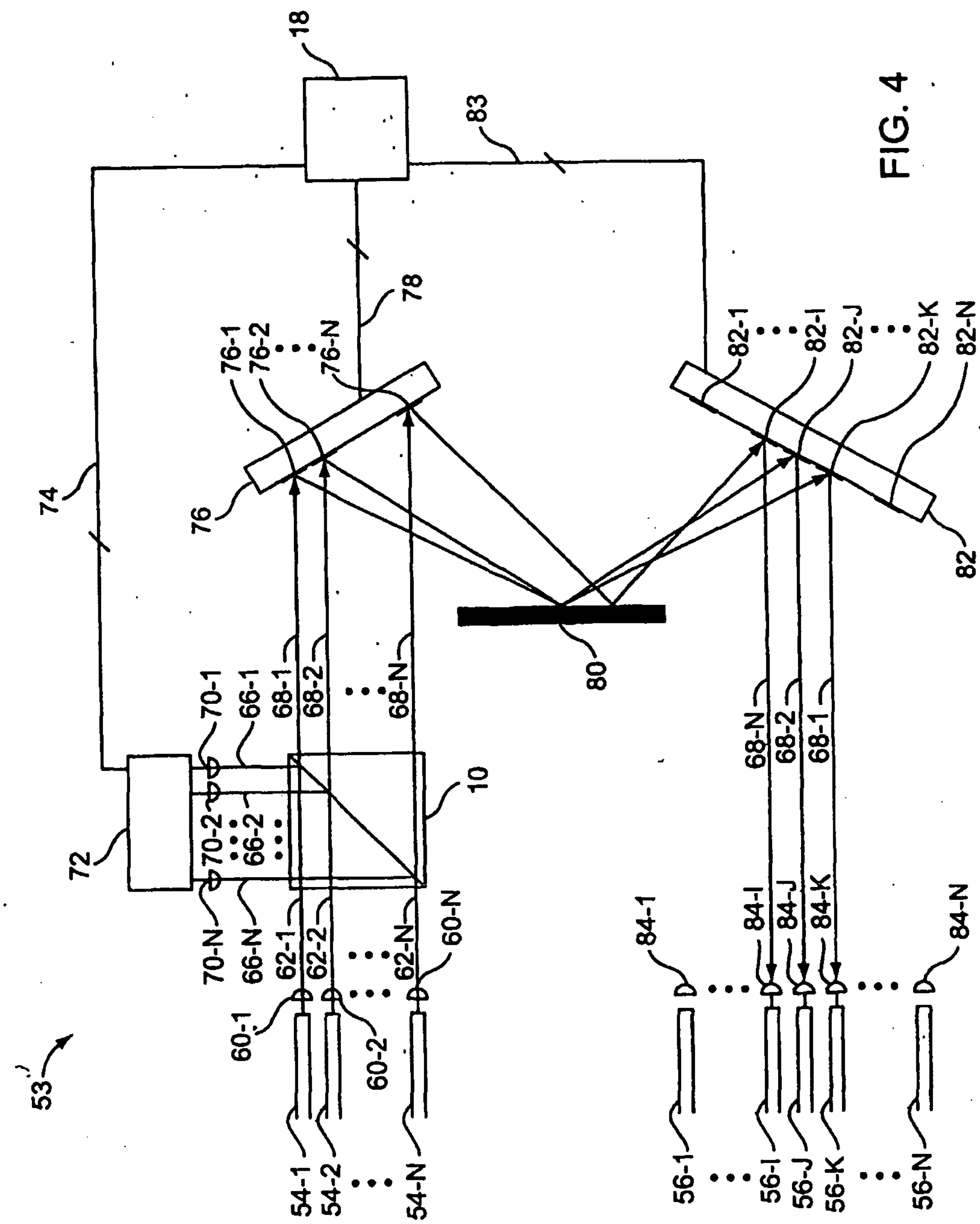
FIG. 3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76-1
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82-1
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66-2
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68-1
68-2
68-N
62-1
62-2
62-N
60-1
60-2
60-N
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54-2
54-N
84-1
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84-K
84-N
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56-I
56-J
56-K
56-N
53

FIG. 4

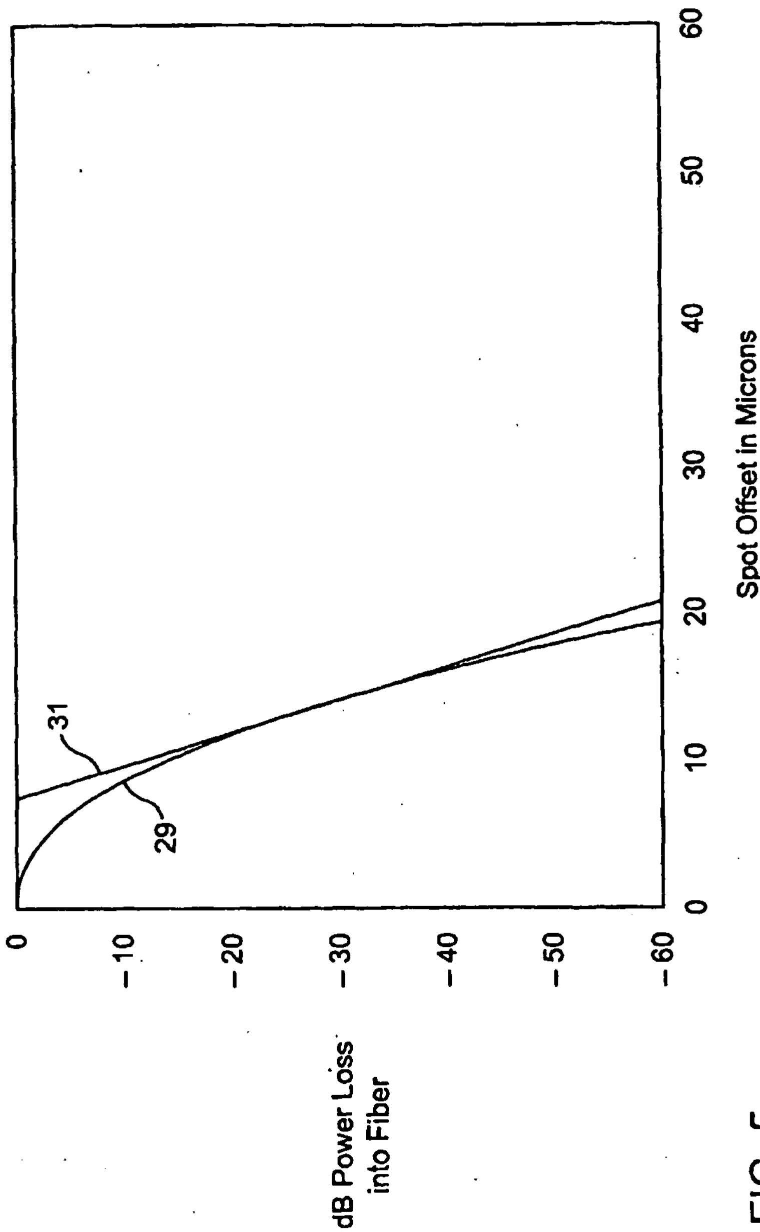
dB Power Loss into Fiber
0
−10
−20
−30
−40
−50
−60
Spot Offset in Microns
0
10
20
30
40
50
60
31
29

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/33514

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G02B 6/26, 6/35
US CL : 385/140, 16, 17, 18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 385/140, 16, 17, 18

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
USPTO APS EAST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,E	US 6,483,962 B1 (NOVOTNY) 19 November 2002 (19.11.2002), see entire document.	1-32
X	US 6,222,954 B1 (RIZA) 24 April 2001 (24.04.2001), see entire document.	1-5,7,9,12-18
X,P	US 2002/0114566 A1 (FAIRCHILD et al) 22 August 2002 (22.08.2002), figures 8-22.	1-32
X	US 6,149,278 A (MAO et al) 21 November 2000 (21.11.2000), see entire document.	1-3,6,10-13,16-18,21
X,P	US 6,374,032 B1 (MAO et al) 16 April 2002 (16.04.2002), see entire document.	1-3,6-13,16-21
X,E	US 2002/0168131 A1 (WALTER et al) 14 November 2002 (14.11.2002), see entire document.	1-4,7,10-18,21-24,26-32

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 07 February 2003 (07.02.2003)	Date of mailing of the international search report 28 MAR 2003
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer ELLEN KIM Telephone No. (703) 308-4946